New results on neutron star low mass transients in the quiescence

S. Campana[a]* L. Stella[b]

[a]INAF – Osservatorio astronomico di Brera, Via Bianchi 46,
I–23807 Merate (LC), Italy

[b]INAF – Osservatorio Astronomico di Roma, Via Frascati 33,
I–00040 Monteporzio Catone (Roma), Italy

We review the main observational properties of neutron star low mass transients in quiescence. We first survey the discoveries of BeppoSAX. We then focus on recent discoveries by Chandra and XMM-Newton, with special emphsasis on the detection of the quiescent counterpart of SAX J1808.4–3658 and the study of variability in the quiescent state.

1. Introduction

Many Low Mass X–ray Binaries (LMXRB) accrete matter at very high rates, and therefore shine as bright X–ray sources only sporadically. Among transient sources are Soft X–ray Transients (SXRTs) host an old neutron star orbiting a low mass star companion (for a review see Campana et al. 1998a). These systems usually alternate periods (weeks to months) of high X–ray luminosity, during which they share the same properties of persistent LMXRBs, to long (1–10 years) intervals of quiescence in which the X–ray luminosity drops by up to 5–6 orders of magnitude.

In recent years the quiescent properties of a handful SXRTs have been studied in some detail thanks to dedicated campaigns carried out with BeppoSAX and RXTE during outburst and observations in quiescence with XMM-Newton and Chandra. Among the main outcomes of these investigations are: 1) SXRT quiescent luminosities are for most cases within a narrow range of $10^{32}-10^{33}$ erg s^{-1} (0.5–10 keV, See Fig. 1); 2) an increasing number of candidate SXRTs in quiescence is being discovered in globular clusters observed with Chandra; 3) the quiescent X–ray spectra of SXRTs display a soft component and in some cases a hard (power-law) component contributing $10-50\%$ of the flux in the 0.5–10 keV band.

Observationally, the soft component can be modelled with a black body of 0.1–0.3 keV temperature and few km radius. Especially promising is the idea that the soft component of SXRTs may be produced from the cooling of the neutron star heated during repeated outbursts (van Paradijs et al. 1987; Stella et al. 1994; Campana et al 1998a). The theory of deep crustal heating by pycnonuclear reactions compares well with the observations (Brown et al. 1998; Campana et al. 1998a; Rutledge et al. 1999; Colpi et al. 2001). In particular, Rutledge et al. (1999) fitted neutron star atmospheric models to the soft component of quiescent spectra of SXRTs and derived temperatures in the 0.1–0.3 keV and radii consistent with the neutron star radius (10–15 km).

The hard component is well described by a power law tail. In the quiescent spectrum of Aql X-1 and Cen X-4 observed by ASCA and BeppoSAX this component is statistically significant (Asai et al. 1996, 1998; Campana et al. 1998b, 2000) with photon index in the 1–2 range. The same power law is needed (even if less significant statistically) in the analysis of Chandra data in order to achieve an emitting radius of the cooling component consistent with the neutron star radius (otherwise the inferred radius would be smaller; Rutledge et al. 2001a, 2001b). In some

*e-mail: campana@merate.mi.astro.it

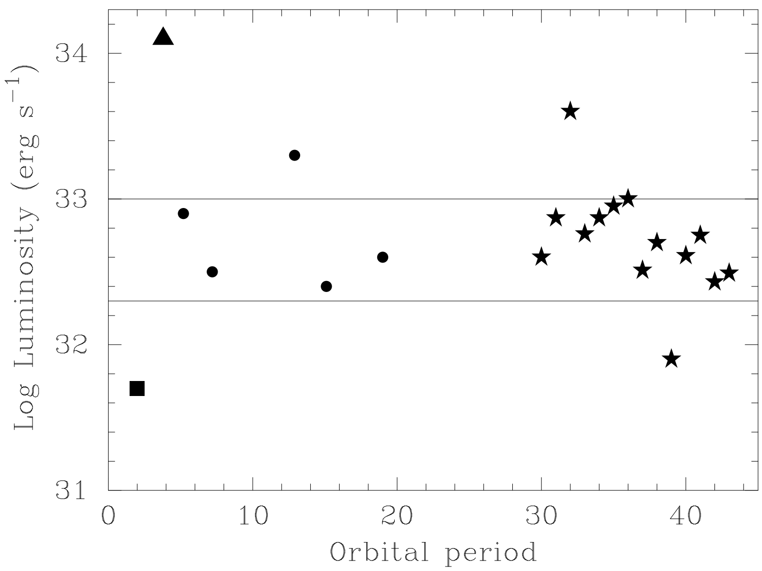

Figure 1. Quiescent 0.5–10 keV (unabsorbed) luminosity of a sample of SXRTs. The triangle is EXO 0748–673 and it is peculiar since it is not clear if it is a true transient system. The five filled circles are well known systems (e.g. Aql X-1, Cen X-4, etc.). The filled square is SAX J1808.4–3658. The stars are globular clusters SXRTs in quiescence recently discovered by Chandra. Their orbital periods are false.

sources in globular clusters instead there is no indication off the presence of a hard tail (e.g. Heinke et al. 2003), as well as in a observation of 4U 1608–52 in quiescence with ASCA (Asai et al. 1996). The nature of this hard component is still uncertain. Models range from Comptonization in a hot corona to Advection/Convection Dominate Accretion Flow (ADAF/CDAF; Menou et al. 1999) to emission from a low luminosity jet (Fender et al. 2003) or shock emission from the neutron star that resumed its radio pulsar activity in quiescence. The latter model envisages a situation similar to that of the eclipsing radio pulsar PSR B1259–63 or of the 'black widow' pulsar PSR B1957+20: a shock at the boundary between the relativistic MHD wind from the radio pulsar and the matter outflowing from the companion star (Tavani & Arons 1997; Tavani & Brookshaw 1991; Campana et al. 1998a). For the model to explain the observed luminosity in the hard power law component of quiescent SXRTs, a few percent of the pulsar spin-down luminosity must be converted into shock emission. Ongoing deep searches in the radio band have not yet revealed any steady or pulsed emission from quiescent SXRTs (Burgay et al. 2003); however free-free absorption due to matter in the binary system and its surroundings might be an important limiting factor in these searches (Stella et al. 1994; Burgay et al. 2003).

2. History

March-April 1997 BeppoSAX observations of Aql X-1 were the first to monitor the evolution of the spectral and time variability properties of a neutron star SXRT from the outburst decay to quiescence. A fast X–ray flux decay was observed, which brought the source luminosity from $\sim 10^{36}$ to $\sim 10^{33}$ erg s^{-1} in less than 10 days (see Fig. 2). This behaviour was later been observed also in other SXRTs as well as Aql X-1 itself.

The X–ray spectrum showed a pronounced hardening in correspondence of the X–ray flux

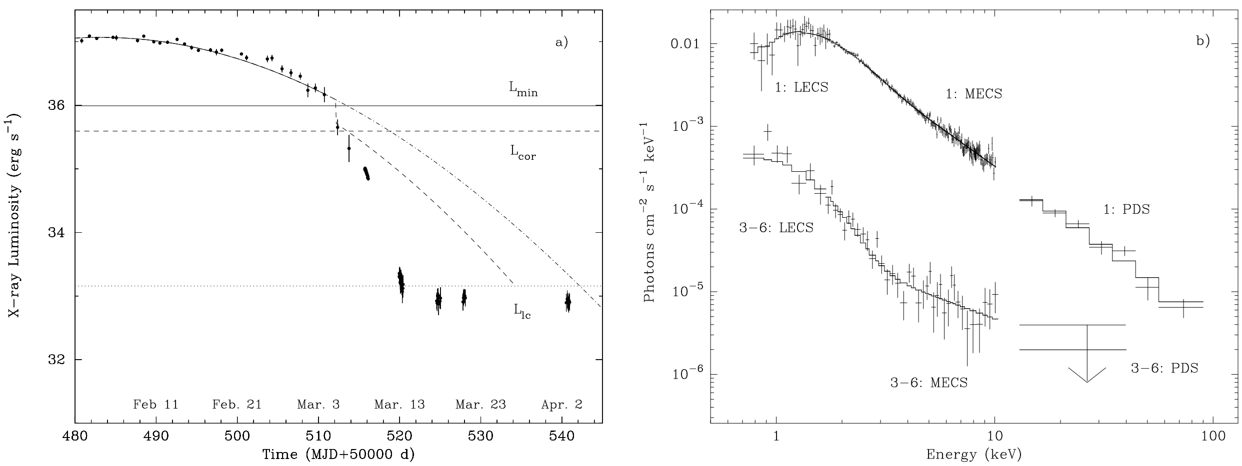

Figure 2. Light curve of the Feb.-Mar. 1997 outburst of Aql X-1 (panel *a*). Data before and after MJD 50514 were collected with the RXTE ASM (2–10 keV) and the BeppoSAX MECS (1.5–10 keV), respectively. The evolution of the flux from MJD 50480 to MJD 50512 is well fit by a Gaussian centered on MJD 50483.2. This fit however does not provide an acceptable description for later times (see the dot-dashed line), not even if the accretion luminosity is calculated in the propeller regime (dashed line). The straight solid line represents the X–ray luminosity corresponding to the closure of the centrifugal barrier $L_{\rm min}$ (for a magnetic field of 10^8 G and a spin period of 1.8 ms) and the straight dashed line the luminosity gap due to the action of the centrifugal barrier, $L_{\rm cor}$. The dotted line marks the minimum luminosity in the propeller regime ($L_{\rm lc}$). Panel *b* shows the BeppoSAX unfolded spectra of Aql X-1 during the early stages of the fast decline (1) and during the quiescent phase (3–6, summed). The best fit spectral model (black body plus power law) is superposed to the data.

turn-off (Zhang et al. 1998; Campana et al. 1998b). This result has been confirmed and extended with RXTE data of the 2002 outburst (Campana et al. 2003). At a luminosity of $\sim 10^{35}$ erg s^{-1} the X–ray spectrum showed a power law high energy tail with photon index $\Gamma \sim 2$ up to 100 keV, markedly different from the thermal spectrum extending up to 30–40 keV observed at luminosities a factor of 10 higher. At even lower luminosities the X–ray spectrum became even harder with $\Gamma \sim 1 - 1.5$. These observations, together with the detection by RXTE of a periodicity of a few milliseconds during an X–ray burst, likely indicate that the rapid flux decay is caused by the onset of the propeller effect arising from the very fast rotation of the neutron star magnetosphere (Campana et al. 1998b; Zhang et al. 1998) and that a further transition may occur approaching quiescence (Campana et al. 1998b). This transition may underline the re-activation of a millisecond radio pulsar in quiescence state of Aql X-1, the relativistic wind of which powers the quiescent X–ray emission.

3. SAX J1808.4–3658

The study of LMXRBs has been revolutionized by the discovery of the first source (the SXRT SAX J1808.4–3658) showing coherent millisecond pulsations in the persistent emission of its outburst state (Wijnands & van der Klis 1998). Other four millisecond pulsating transients have later been discovered.

SAX J1808.4–3658 showed the same decrease to quiescence as Aql X-1 (Gilfanov et al. 1998) with a hard power law appearing at luminosities

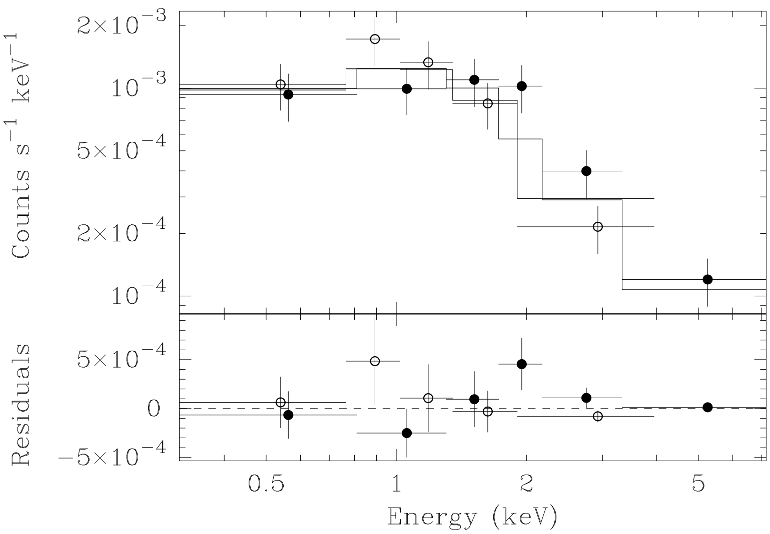

Figure 3. MOS1 (open dots) and MOS2 (filled dots) spectrum of SAX J1808.4–3658. Overlaid is the fit with an absorbed power law model described in the text. In the lower panel are reported the residuals of the fit.

of $\sim 5\times10^{35}$ erg s^{-1} (Gilfanov et al. 1998). A few attempts to reveal SAX J1808.4–3658 in quiescence have been carried out with ASCA and BeppoSAX (Stella et al. 2000; Wijnands et al. 2002a). These observations revealed a source at a luminosity of $\sim 10^{32}$ erg s^{-1}; yet the field is crowded, source confusion a problem for the ~ 1 arcmin resolution achieved by BeppoSAX and ASCA and no firm conclusions could be drawn. An XMM-Newton observation with a high signal to noise revealed SAX J1808.4–3658 in quiescence isolated, but a nearby source (about 1 arcmin) can have altered the position and the flux observed with previous instruments (Campana et al. 2002). The 0.5–10 keV unabsorbed luminosity is 5×10^{31} erg s^{-1}, a relatively low value compared with other neutron star SXRTs. Moreover, at variance with other SXRTs, the quiescent spectrum of SAX J1808.4–3658 was dominated by a hard ($\Gamma\sim1.5$) power law with only a minor contribution ($\lesssim 10\%$), if any, from a soft black body/neutron star atmosphere component (Fig. 3). If the power law originates in the shock between the wind of a turned-on radio pulsar and matter outflowing from the companion, then a spin-down to X–ray luminosity conversion efficiency of $\eta\sim10^{-3}$ is derived; this is in line with the value estimated from the eclipsing radio pulsar PSR J1740–5340 (D'Amico et al. 2001). Within the deep crustal heating model, the faintness of the blackbody-like component indicates that SAX J1808.4–3658 may host a massive neutron star ($M \gtrsim 1.7\ M_\odot$). In fact this is the only way to have a rapid cooling thanks to direct Urca process and in turn neutrino cooling.

4. Variability in quiescence

Short term variability is potentially a powerful tool for the study of the emission mechanism(s) responsible for the SXRTs quiescent emission. A factor of 3 variability over timescales of days (Campana et al. 1997) and 40% over 4.5 yr (Rutledge et al. 2001b) was reported in Cen X-4. Several other neutron star systems have also been found to be variable in quiescence by factors of 3–5 (e.g. Rutledge et al. 2000) but data have been collected over several years and with different instruments. Interesting results have been recently found thanks to the observations of well known systems with Chandra and XMM-Newton.

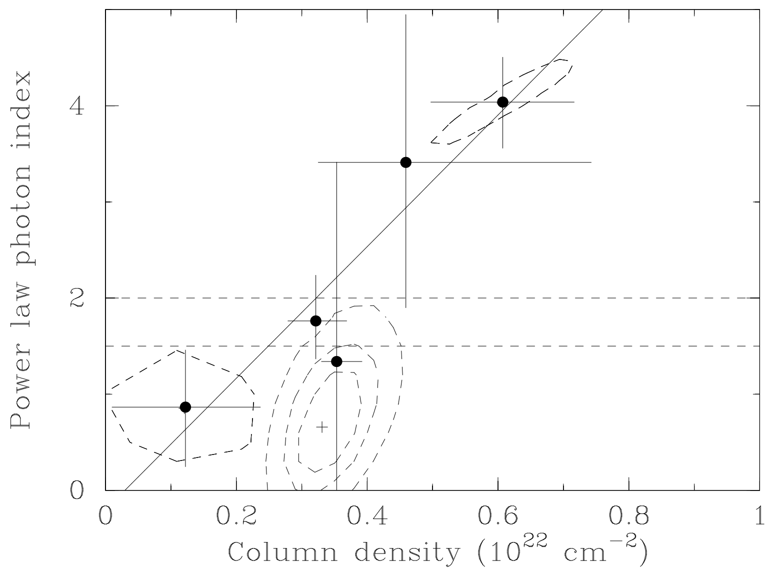

Figure 4. Power law photon index vs. column density correlation of the five Aql X-1 observations. Overplotted is the best linear fit. Dashed lines indicate the range over which the synchrotron emission model likely applies. On the hardest and softest observations $1\,\sigma$ countours have been superposed. The 1, 2, $3\,\sigma$ countours obtained fitting the entire set of data with a single power law and column density is also reported.

After years of persistent emission at a high level, KS 1731–260 turned to quiescence (Wijnands et al. 2001; Burderi et al. 2002). The source was observed first with Chandra and 6 months later with XMM-Newton. The quiescent luminosity decrease by a factor of 2–5 (Wijnands et al. 2002b). In the cooling neutron star model, this decrease implies that the crust of the neutron star cooled down rapidly between the two epochs, indicating that the crust has a high conductivity. Further monitoring of KS 1731–260 in quiescence can provide crutial information on the crust conductivity and level of impurities (Rutledge et al. 2002a). A similar turn-off of the X–ray luminosity after years of activity occurred in X1732–304 (in Terzan 1; Wijnands et al. 2002c) and MXB 1659–29 (after 2.5 yr of activity, Wijnands et al. 2002d). These sources may represent a new population of long-lasting transients.

Rutledge et al. (2002b) analyzing Chandra data of the Aql X-1 quiescent phase after the November 2000 outburst found a variable flux and X–ray spectrum. They interpreted these variations in terms of variations of the neutron star effective temperature, which changed from 130^{+3}_{-5} eV, down to 113^{+3}_{-4} eV, and finally increased to 118^{+9}_{-4} eV. Interestingly, during the last observation they also found short-term ($< 10^4$ s) variability (at 32% rms). These data are the first to show an increase of the quiescent flux in the quiescent SXRT. The latter result has a direct impact on the quiescent emission models, since no known mechanism associated with crustal heating can account for this variability. Rutledge et al. (2002b) suggested that accretion might occur during the Aql X-1 quiescent state and variations have can be ascribed to a variable mass inflow rate.

Campana & Stella (2003) reanalyzed the Chandra spectra of Aql X-1, together with a long BeppoSAX observation in the same period, and propose a different interpretation of the spectral vari-

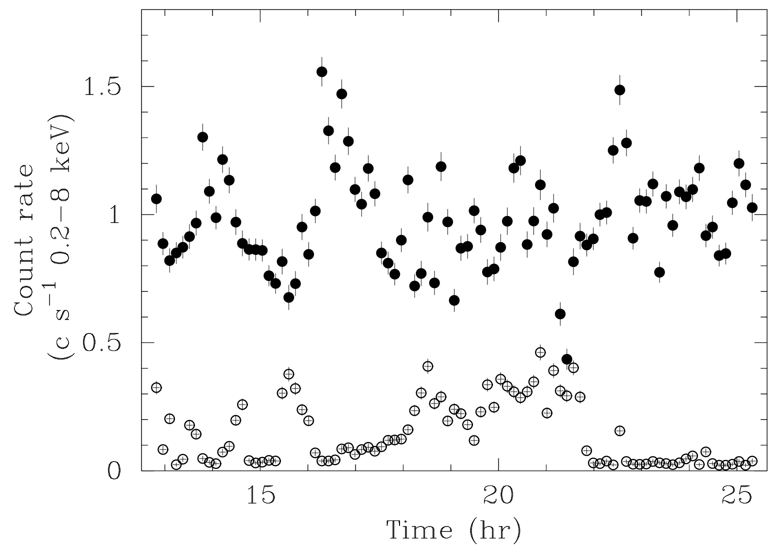

Figure 5. Background subtracted 0.2–8 keV pn light curve of Cen X-4. The bin size is 500 s. Open dots represent the background light curve scaled to the source extraction area (which has been already subtracted in the light curve above).

ability: that this is due to correlated variations of the power law component and the column density (> 5, a part of which might be intrinsic to the source), while the temperature and flux of the neutron star atmospheric component remained unchanged (Fig. 4). The power law slope vs. column density behaviour is in qualitative agreement with that observed from the radio pulsar binary PSR 1259–63, lending support to the idea that the power law component arises from emission at the shock between a radio pulsar wind and inflowing matter from the companion star.

Thanks to XMM-Newton large throughput, Cen X-4 was observed with the highest signal to noise ever. A ~ 13 hr observation revealed rapid (> 100 s), large ($45 \pm 7\%$ rms in the $10^{-4} - 1$ Hz range) intensity variability, especially at low energies (Fig. 5). In order to investigate the cause of this variability, Campana et al. (2003) divided the data into intensity intervals and fit the resulting spectra with the canonical model for neutron star transients in quiescence, i.e. an absorbed power law plus a neutron star atmosphere model. Variations across different spectra can be mainly accounted for by a variation in the column density together with another spectral parameter (Fig. 6). Based on the available spectra, a variation of the power law could not be preferred over a variation in the temperature of the atmosphere component (even if the first is slightly better in terms of reduced χ^2). This variability can be accounted for by accretion onto the neutron star surface (e.g. Rutledge et al. 2002b) or by the variable interaction between the pulsar relativistic wind and matter outflowing from the companion in a shock front (e.g. Campana & Stella 2003).

5. Conclusions

The study of SXRTs in quiescence is revealing a rich phenomenology. For the interpretation of this, different emission mechanism(s) and underlying different physical scenarios are actively debated. These depend on the influence of the neutron star rotation and magnetic field on the infalling matter as well as the physics of deep

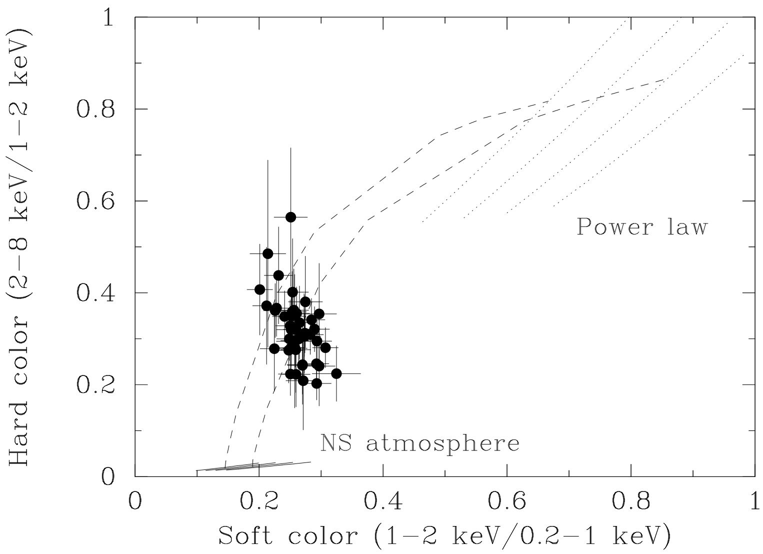

Figure 6. Color-color diagram of the pn background subtracted light curve. The soft color is defined as the ratio of the counts in the 0.2–1 keV to 1–2 keV, the hard color as the ratio of the counts in the 2–8 keV to 1–2 keV. On top of this we depict hardness ratios for an absorbed power law model (with photon index from 1.2 to 2) and an absorbed neutron star atmosphere model (with temperatures from 70 to 100 eV) for different values of column densities (3, 5, 7, 9×10^{20} cm^{-2}, dotted lines). Two different (dashed) curves connect the single component models with increasing contribution from the two for column densities of 5 and 9×10^{20} cm^{-2}.

Table 1
Standard spectral models fits for the high and low count rate interval.

Model	N_H (10^{20} cm^{-2})	kT (eV)	Photon index (hard component)	$\chi^2_{\rm red}$ (d.o.f.)	N.h.p.
Low	6.0 ± 2.9	87 ± 1	1.53 ± 0.17 (40%)	2.60 (450)	0%
Medium					
High					
Low	15.1 ± 3.6	78 ± 9	1.60 ± 0.14 (35%)	1.51 (448)	0%
Medium	8.9 ± 4.3				
High	4.4 ± 3.4				
Low	5.1 ± 2.6	86 ± 7	1.47 ± 0.13 (46%)	1.02 (446)	37%
Medium	4.6 ± 2.6	91 ± 5	(38%)		
High	6.0 ± 2.1	99 ± 7	(30%)		
Low	9.6 ± 4.6	85 ± 6	1.32 ± 0.19 (33%)	1.03 (444)	34%
Medium	5.4 ± 3.7		1.62 ± 0.16 (42%)		
High	4.6 ± 3.8		2.11 ± 0.20 (53%)		

In the case of a varying neutron star atmosphere model the radius 9.7 ± 2.4 km (intrinsic radii), whereas for a varying power law we have a radius of 11.5 ± 6.0 km.

crustal heating during intense accretion episodes. In the last few years, mainly after the discovery of coherent pulsations in the transient SAX J1808.4–3658, a large interest in these sources has grown. Chandra and XMM-Newton (quiescence) as well as BeppoSAX and RXTE (outburst) observations yielded many interesting results. In particular, the discovery of a sizeable population of candidate SXRTs in globular clusters is providing important new clues on the statistical properties of SXRTs in quiescence. Besides the most studied sources, peculiar behaviours are being found in other sources such as SAX J1808.4–3658 itself, characterized by a factor of 2 lower mean luminosity and, more importantly, a spectrum dominated by the power law component.

On the other hand, in depth studies of as well known sources with Chandra and XMM-Newton are still providing new and unexpected results. In the case of Aql X-1 monitoring its quiescent state with Chandra led to the discovery of luminosity and spectral variability over a month timescale. This can either been interpreted as accretion occurring at these low rates (with an uninfluent magnetic field, Rutledge et al. 2002b) or as correlated variability in the quantity of matter around the system and change in the power law slope due to the interaction of a relativistic pulsar wind with this matter (Campana & Stella 2003). In the case of Cen X-4 an XMM-Newton observation disclosed rapid ($\lesssim 100$ s) X–ray variability, the nature of which, while still uncertain, can be accounted for by the two different mechanisms discussed above (Campana et al. 2003).

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